March 2000

Science & Technology REVIEW

U.S. Department of Energy's
Lawrence Livermore
National Laboratory

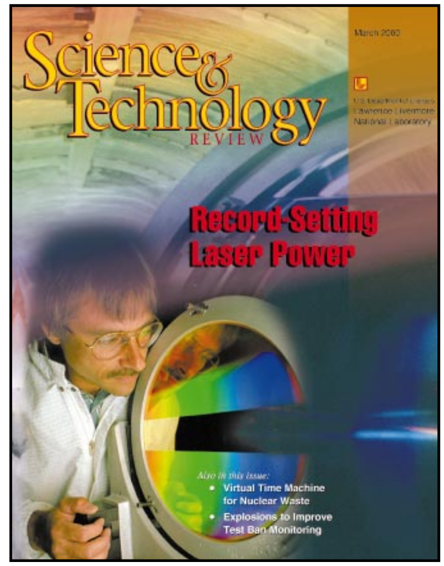
Record-Setting Laser Power

Also in this issue:

- **Virtual Time Machine for Nuclear Waste**
- **Explosions to Improve Test Ban Monitoring**

About the Cover

Chemical engineer Jerald Britten examines a diffraction grating for Livermore's Petawatt laser, which operated as the most powerful laser in the world from May 1996 to May 1999. The grating managed the Petawatt laser's potentially lens-damaging power through the technique of chirped-pulse amplification, described in the article beginning on p. 4. Also described are experiments demonstrating the laser's capability to split atoms, generate antimatter, and behave like a powerful ion accelerator. The Petawatt laser set Livermore's latest record in laser peak power.



About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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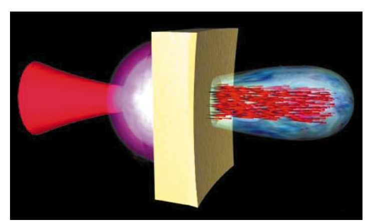

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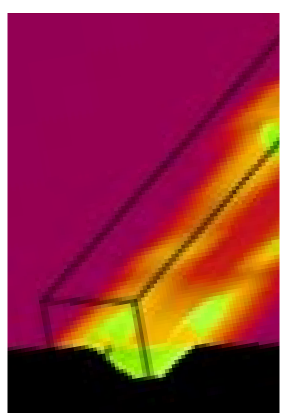

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New ideas about Earth's formation

Scientists have long wondered why the contents of Earth's atmosphere doesn't match the contents of the rest of the solar system. Late last year, Lawrence Livermore scientists made a discovery that may lead to a new model of how Earth was formed and may, in turn, explain this puzzle.

Livermore's Marc Caffee and his team described in the September 24, 1999, issue of *Science* their discovery of xenon gas seeping out of gas wells in Colorado, New Mexico, and Australia. The gas is of the same form as xenon found in the sun and throughout the solar system, but different from that found in Earth's atmosphere.

The discovery hints at a more complex picture of how Earth's atmosphere evolved. Scientists have long posited that Earth and the rest of the solar system formed about 4.5 billion years ago from a disk of dust swirling around the newly born sun. Earth formed itself into separate layers—core, mantle, and crust. Gases bubbled out of the mantle to create an atmosphere around the planet.

The discovery of primordial xenon gases suggests that "the old paradigm of one big happy uniform mantle, and the atmosphere coming out of all or part of it, is too simple," said Caffee. If the gases, which are thought to come from the mantle, are similar to what is found in meteorites but not to what's found in Earth's atmosphere, did something happen to Earth to alter its atmosphere? Or is it that the mantle is much more complex than previously thought?

One notion is that the early Earth may have been put together from a plethora of materials that left different chemical signatures in the mantle. Earth's atmosphere may have come from only a part of the mantle, a part that did not include the primordial gases.

At any rate, those gases provide a view of the planet's earliest days. "It's kind of cool that the stuff is down there," said Caffee.

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A primer on parallel computing

The newly published *Industrial Strength Parallel Computing* (Morgan Kaufmann Publishers, November 1999), edited by Livermore's Alice Koniges, sounds daunting. But the book really aims to make software developments in parallel computing more accessible to the growing numbers of parallel computing practitioners.

Back in the 1960s, parallel computing existed but wasn't much applied. In changing computer processing from step-by-step sequential calculations to independent but simultaneous calculations of many parts of a large problem, the new technique demanded increased processing power and new software to handle a new kind of problem management.

In the beginning, parallel computing was largely relegated to research universities and national laboratories. The introduction of PCs, which gave more people access to many inexpensive processors, pushed more researchers to develop software for parallel computing.

Among the efforts to enhance software developed by national laboratories and universities for industrial applications was the Parallel Applications Technology Project, a collaborative effort funded by the Department of Energy, similar agencies worldwide, Cray Research, and industrial partners. The book edited by Koniges grew out of the project when its leaders thought their results "needed to be collected in more than a series of articles in scientific journals."

Koniges says the book represents the expertise of some 72 contributors from national laboratories, universities, and private industry. Eleven of its 25 chapters have Livermore authors. Livermore contributors include Steve Ashby, Chuck Baldwin, William Bosl, David Eder, Robert Falgout, Morris Jette, Douglas Rotman, Steven G. Smith, Vijay Sonnad, John Tannahill, Andrew Thompson, and Lin Yang.

Koniges has spent most of her 15 years at Livermore in developing leading-edge scientific computing technology. She is an internationally recognized authority on parallel applications development.

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Reaping Unexpected Benefits from the Petawatt Laser Breakthrough

PERSISTENCE, creativity, luck, and old-fashioned hard work are the essential elements of any success story. They were all present in abundance during the development and use of Livermore's Petawatt laser. They had to be, because the project faced some formidable technical challenges. It was considered to be such a high-risk undertaking that, although initially proposed in 1987, work on it did not begin until 1993, when funding was provided by Livermore's Laboratory Directed Research and Development program. The prospect of doing laser experiments at an irradiance over ten thousand times greater than had ever been achieved made the project too exciting to pass up.

Seven years later, it is clear that the science and technology that emerged through developing the Petawatt laser will benefit the scientific community, U.S. industry, and the Laboratory for years to come.

To produce petawatt (quadrillion-watt) pulses, the development team had to produce diffraction gratings much larger and more advanced than what was the state of the art. Such gratings manipulate the delivery and distribution of laser light so that powerful laser pulses don't self-focus and damage the laser optics. The gratings necessary for the Petawatt laser simply didn't exist because they had to contain millions of grooves, each only a fraction of a micrometer wide, and be nearly an order of magnitude larger than any grating previously produced. Moreover, these gratings had to exhibit extremely high diffraction efficiency and operate at a power density much higher than had ever been achieved.

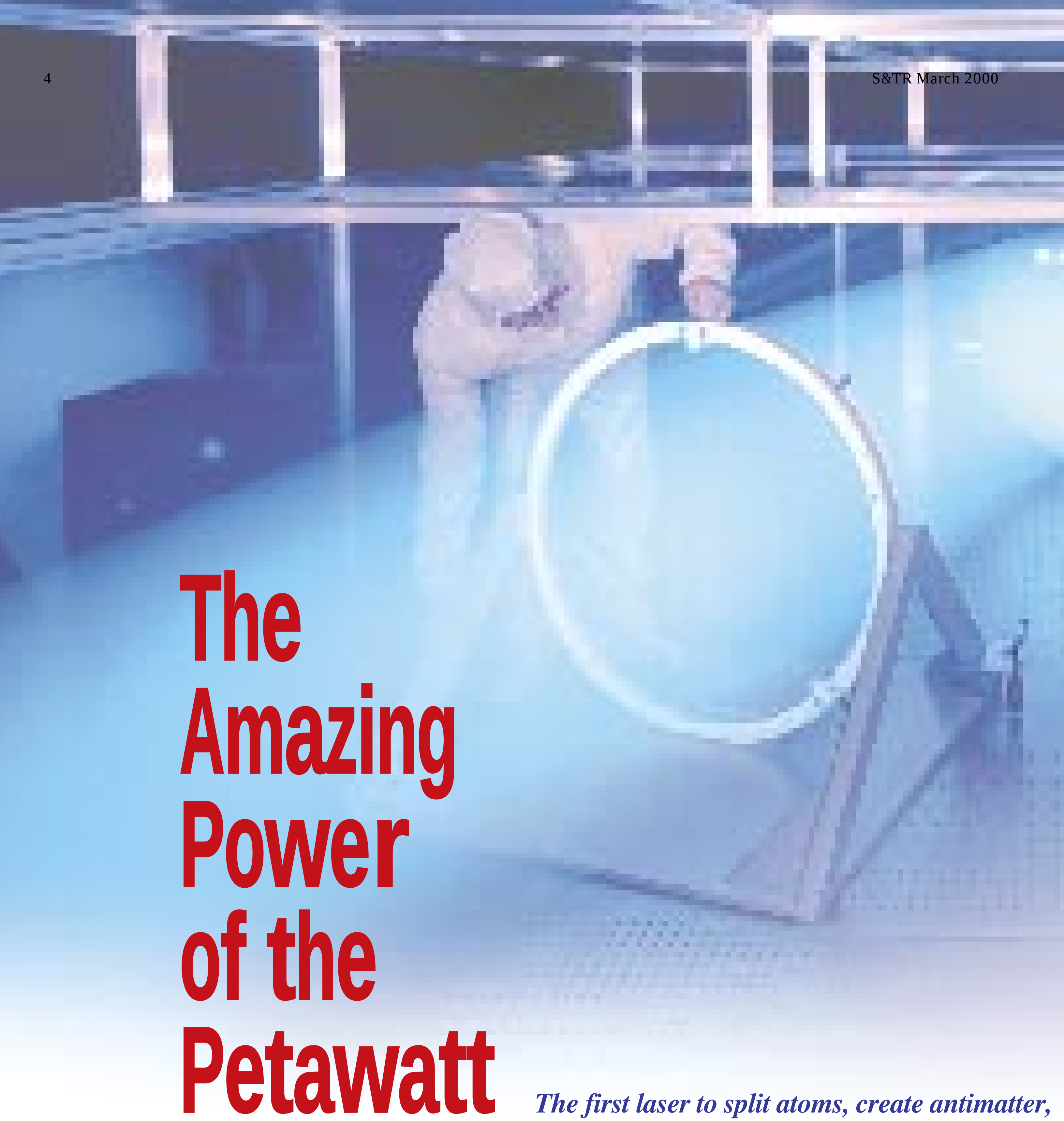
The development of facilities and know-how to manufacture these gratings has made Livermore into one of the world's centers for the development and fabrication of diffractive optics. Since completion of the Petawatt gratings, we have developed diffractive optics for laboratories throughout the world, numerous companies, and several government agencies, as well as for Livermore's next superlaser, the National Ignition Facility.

The discovery that laser-damage mechanisms are different at very short pulse durations led to an important new application for lasers. Livermore researchers found that materials machined with ultrashort laser pulses are virtually undamaged, because those pulses are too brief to transfer heat or shock to the materials. This discovery is now being applied in the Lifetime Extension Program for stockpiled weapons, and we are refining the technology for use in large-scale commercial and defense applications.

The scientific discoveries emerging from Petawatt laser experiments will be analyzed for years to come. Although the Petawatt laser was developed originally to perform basic research on the fast ignitor concept for inertial confinement fusion, physicists Mike Perry and Joe Sefcik proposed its use as a source of intense, high-energy x-radiation. As they were demonstrating the Petawatt laser's utility as an intense x-ray source to support the Department of Energy's Stockpile Stewardship Program—to protect the viability of the nation's nuclear stockpile—Livermore scientists observed laser-initiated nuclear reactions, high-energy electron production, and the formation of positron–electron pairs and proton beams far brighter than those produced by any accelerator. These discoveries are described more fully in the article beginning on p. 4.

The Petawatt laser was shut down at the height of its use in May 1999 because the Nova laser facility in which it was housed was being closed to make room for the National Ignition Facility. However, the discoveries enabled by the Petawatt laser will continue to be pursued at new petawatt-class laser facilities under construction in Germany, France, England, and Japan.

■ George Miller is Associate Director for National Security and Acting Associate Director for Laser Programs.



The Amazing Power of the Petawatt

The first laser to split atoms, create antimatter,

THE intense beam of Livermore's Petawatt laser was powerful enough to break up atoms by causing reactions in their nuclei. Accelerated by the laser, electrons traveling at nearly the speed of light collided with nuclei in a gold foil target, producing gamma rays that knocked out some of the neutrons from other gold nuclei and caused the gold to decay into elements such as platinum. Gamma rays also zoomed in on a layer of uranium sitting behind the gold and split uranium nuclei into lighter elements. Before the Petawatt, all of these effects had been solely in the domain of particle accelerators or nuclear reactors.

Accelerated to energies exceeding 100 megaelectronvolts, the electrons in the gold targets produced high-energy x rays. These in turn decayed into pairs of electrons and their antimatter counterparts, positrons, in such large numbers as to possibly generate an electron–positron plasma, never before created in the laboratory. An intense beam of protons also turned up. Not only was the Petawatt the most powerful laser in the world, but, unexpectedly, it also was a powerful ion accelerator.

Livermore's Petawatt laser operated for three years, until its last shot was fired on May 27, 1999. At full energy of about 680 joules, the shots delivered more than a quadrillion watts (or petawatt, which equals 10^{15} watts) of power, exceeding the entire electrical generating capacity of the U.S. by more than 1,200 times. But the Petawatt's shots lasted for just a fleeting moment—less than a trillionth of a second, or 440 femtoseconds to be precise.

and generate an intense, well-focused proton beam—such was the power of the Petawatt.

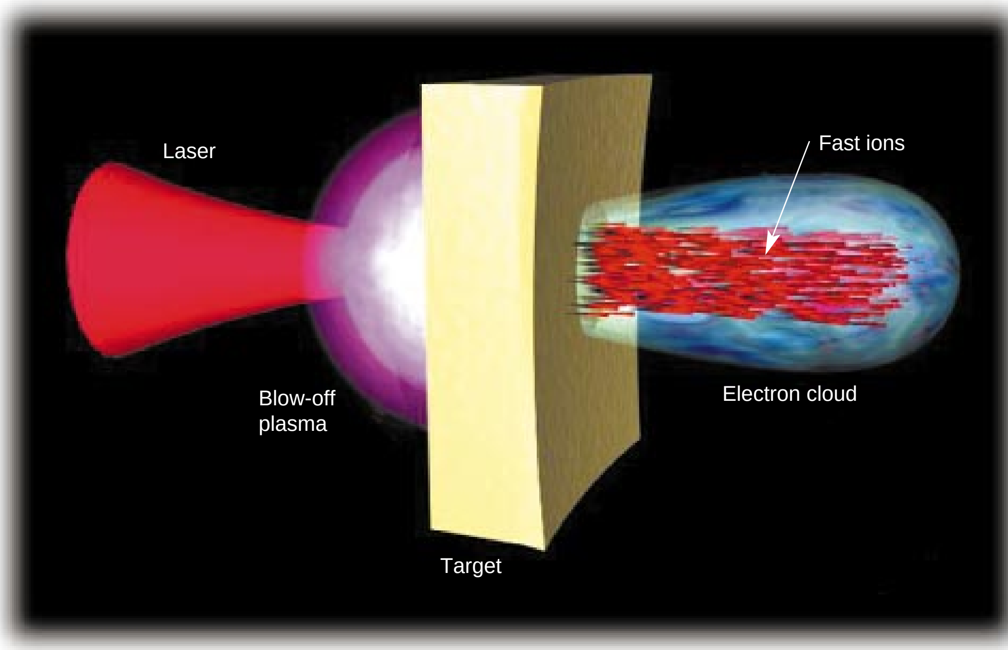
The Petawatt laser was developed originally to test the fast ignition path to inertial confinement fusion in the ongoing attempt to ignite a pellet of hydrogen fuel and harness the energy that powers the sun. The power of the Petawatt also opened up entirely new physical regimes to study. Now scientists can use lasers, not just particle accelerators, to study high-energy-density physics and the fundamental properties of matter. They may also be able to recreate in the laboratory the energized plasmas around black holes and neutron stars for astrophysical research.

The Petawatt was developed by a team of physicists, engineers, and technicians under the leadership of physicist Michael Perry. Going into the project, the team knew that the ultrashort pulses and extremely high irradiance (power per unit area) of the Petawatt would push electrons almost to light speed with power densities never before seen in the laboratory. The researchers hoped to bring the fast ignitor concept for laser fusion closer to reality and planned to study the Petawatt as an x-ray source for flash x-radiography. But the Petawatt also brought several surprises and unusual spinoffs. Surprises are common enough in physics research, but the Petawatt created more than its fair share.

Just the Latest Record-Breaker

After four years of development, the laser achieved petawatt peak power on May 23, 1996, and became the latest in Livermore's long line of record-breaking lasers, each with greater peak power than its predecessor. Recognized in 1966 as one of the most significant advances in laser technology, the Petawatt operated on one arm of Livermore's 10-beam Nova laser until Nova was dismantled in 1999 to make way for the National Ignition Facility. The Petawatt laser combined the short pulses available from titanium-doped sapphire (Ti:sapphire) lasers and chirped-pulse amplification in the Nova glass laser to create high-powered, extremely short pulses with a peak power more than an order of magnitude greater than Livermore's previous record of 100 terawatts, set in 1995. (See *S&TR*, December 1996, pp. 4–11.)

Without chirped-pulse amplification, laser pulses of extremely high power density (gigawatts per square centimeter) can rapidly self-focus and severely damage such optical components as amplifiers, lenses, and mirrors. The technique of chirped-pulse amplification stretches a low-energy laser pulse by more than 25,000 times in duration prior to amplification and afterward recompresses it to near its original duration. Because the pulse passes through the laser optics when it is long, there is no damage to expensive optics. Pulse recompression takes place in a vacuum because by this time, the laser is too intense to pass through any material (including air) without causing damage.



In laboratory experiments, the Petawatt laser's tremendous power produced intense beams of protons, proving the laser to be a powerful ion accelerator.

Crossing the Relativistic Barrier

The Petawatt laser achieved a focused power density approaching 10^{21} W/cm^2 (almost a sextillion watts of energy concentrated on a square centimeter) and an energy density of 30 billion joules in a cubic centimeter—far exceeding the energy density inside stars. The associated electric fields are so strong—approximately a thousand times stronger than those that bind electrons to atomic nuclei—that they strip electrons off atoms and accelerate them to relativistic velocity (that is, comparable to the speed of light). The acceleration happens within a microscopic scale, compared to that in conventional particle accelerators. The enormous electric fields impart huge "quiver" energy to the free electrons in the plasma, which flings some of the electrons out of their oscillation. This then causes laser energy to convert to electron thermal energy, which in turn heats the ions and forms dense, high-temperature plasmas.

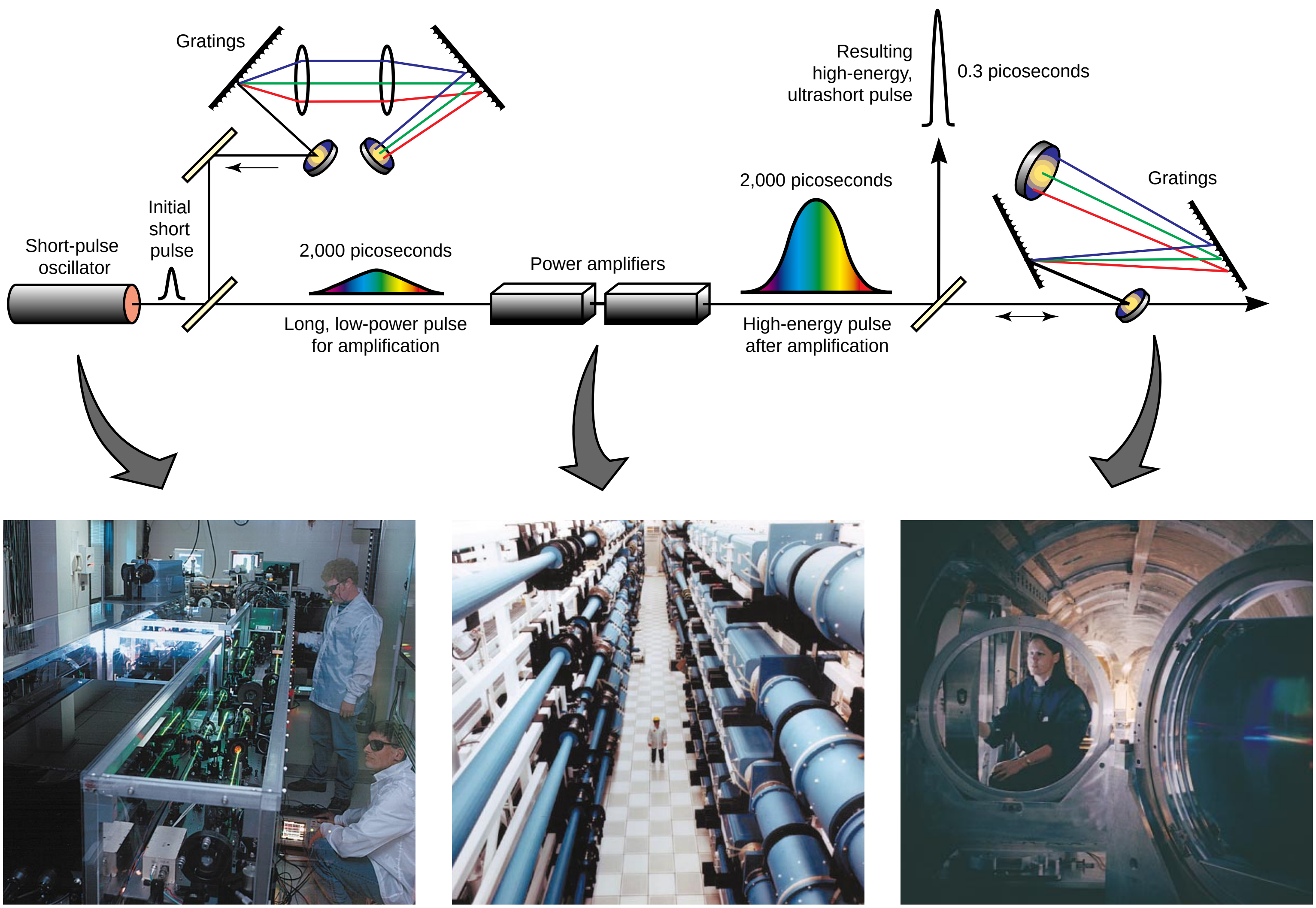
When particles are moving at almost the speed of light, strange things happen. In this relativistic regime, the electron's energy exceeds its "rest mass" (that is, the energy that would be released if it were turned into pure energy, $e = mc^2$). Its mass also increases with increasing speed.

Another feature of the high energy density is the correspondingly high pressure. The light pressure of the Petawatt beam is approximately 30 petapascals, or about 300 billion times greater than Earth's atmospheric pressure at sea level. This huge pressure works like a snow plow, effectively shoving the plasma forward. As a result, the light can penetrate to a density much greater than is possible with normal lasers. The effects of using the light pressure to confine and even shape near-solid-density plasmas may have applications in inertial confinement fusion.

Unexpected Discoveries

Early experiments showed that when the Petawatt's intense beam hit a high-atomic-number target such as gold, very energetic electrons were produced. The energies were as high as 100 megaelectronvolts, with average energies ranging from 1 to 10 megaelectronvolts. Petawatt research first examined the characteristics of these relativistic electrons, which had never before been seen in such huge numbers in laser experiments.

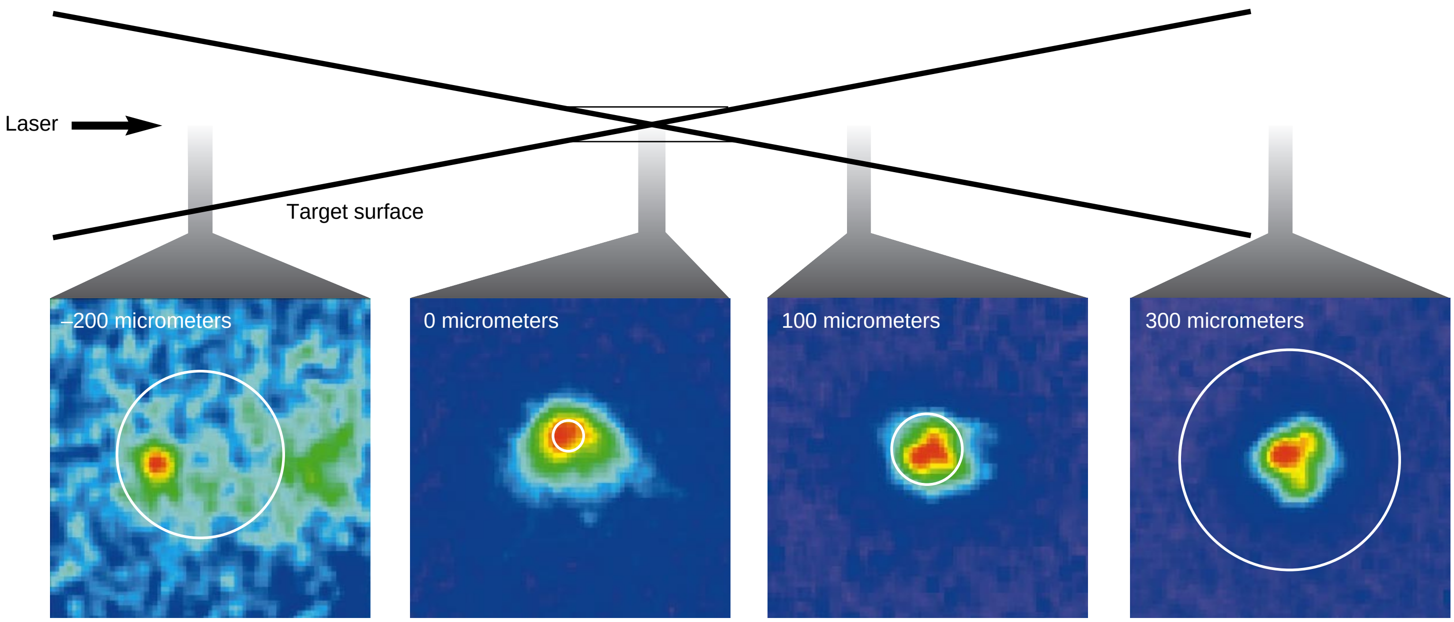
To determine the electron energies, two electron spectrometers were mounted at angles to the target. Each one used magnets to separate electrons



The chirped-pulse amplification technique makes it possible for the Petawatt laser's high-power pulses to pass through laser optics without damaging them. Before amplification, low-energy laser pulses are passed through diffraction gratings to stretch their duration by as much as 25,000 times. After amplification, the pulses are recompressed back to near their original duration. Because the pulses pass through the laser optics when they are long, they cause no damage.

and positrons. Each also incorporated a pair of nuclear emulsion track detectors to record the tracks of each charged particle. The particle tracks were counted by a group at the NASA Marshall Space Flight Center in Huntsville, Alabama, which routinely monitors high-energy radiation from space.

Electron energies greater than about 2 megaelectronvolts produce gamma rays that can be transformed into pairs of electrons and positrons (pair production). But using some very thin gold targets, physicist Tom Cowan and others found more positrons than expected, which may indicate that they had created an electron–positron plasma. In these extraordinarily high-



The Petawatt beam undergoes relativistic self-focusing, seen here in x-ray images of the target in which a heated region is made smaller than the optical focal spot (white circles) when the target is 300 micrometers beyond the focal spot.

The Laser Cutting Revolution

A primary spinoff from the Petawatt laser has been the development of ultrashort-pulse lasers for high-precision laser cutting and machining. Brent Stuart and others first observed the laser's cutting capabilities during early research on the laser damage threshold for a variety of optical materials. Using laser pulses ranging from 0.1 to 1,000 picoseconds, they observed a fundamental change in the damage mechanism when the pulse length is less than about 20 picoseconds. The ultrashort pulses are too brief to transfer heat or shock to the material being cut, so cutting, drilling, and machining can occur with virtually no damage to surrounding material.

This discovery was put into practical use in developing the first femtosecond laser cutter for use as a precision cutting tool in dismantling weapons at DOE's Y-12 Plant. For Livermore's High Explosives Application Facility, Stuart and his team developed a second-generation system that can cut high explosives without deflagration or detonation. Third-generation ultrashort-pulse machine tools are now being developed at Livermore for a variety of high-precision machining and medical applications.

The laser can also be used to produce high-quality thin films by using the laser to ablate (blow off) material. The high-energy plasma generated during ablation enables the deposition of smooth films containing no particulates.

When the laser is attached to a spectrometer, the operator can identify what material is being cut by watching the changing spectra. A surgeon could thus carefully differentiate between bone and muscle, which have very different spectra. This differentiation could also be useful in paleontology excavations for cutting away rock without damaging bones embedded in them.

energy plasmas, which are believed to exist near black holes and neutron stars, positrons are continually being created as particles collide with one another. Next-generation petawatt-class lasers producing even higher irradiance than the Petawatt should be able to create these antimatter plasmas in the laboratory, providing a new tool for astrophysical research.

To study the angular pattern of the beam of electrons, one researcher installed a conical assembly behind the target. Tantalum of varying thicknesses was layered together with radiochromic film, which recorded the angular pattern of relativistic electrons escaping a variety of targets. The figure below shows the results of a typical experiment using a 125-micrometer-thick gold target.

Researchers were puzzled by the dark spot that is visible in the figure. They first took it to be a particularly well-focused part of the electron beam. At the same time, a radiation physicist began observing a large number of defects in a type of plastic (Cr-39) used to detect particles, which could only have been induced by high-energy protons. At this point, experimental team leader Mike Key reanalyzed the radiochromic pictures and showed that the beam could be explained as a proton beam. Several specific tests were devised to confirm this hypothesis.

Conclusive evidence that this beam was composed of protons was obtained from a series of nuclear chemistry experiments. The experimental team used a multilayer detector of titanium and beryllium and radiochromic film to observe the nuclear reactions induced in both the titanium and the beryllium, which could only be produced by protons with energies greater than 40 megaelectronvolts. Combined with several other diagnostics, these measurements showed that the proton beam must contain more than 30 trillion protons or over 40 joules of energy (integrated over the proton spectrum).

Further evidence for the proton beam was provided by a proton-sensitive nuclear emulsion strip added to the magnetic spectrometer shown in the figure in the middle of p. 10. Because protons have about 1,800 times the mass of electrons and are deflected less as they travel through the magnetic field in the spectrometer, a proton-sensitive strip was attached at the far end of the spectrometer. The emulsion was turned black by the extraordinary number of protons, giving evidence of proton energies greater than 55 megaelectronvolts.

Delivered in the short duration of the Petawatt's laser pulse, the proton beam current is over 10 million amperes, making the Petawatt one of the world's most powerful ion accelerators.

Experiments with wedge-shaped targets showed that most of the proton beam was emitted perpendicular to the rear surface of the target, independent of how the target was aligned to the laser beam. This finding is important for understanding how the beam is generated. More work is needed to characterize the beam, but such a powerful proton beam will surely find many uses. It might replace the front end of large accelerators or be used itself as an ignitor in fast ignition.

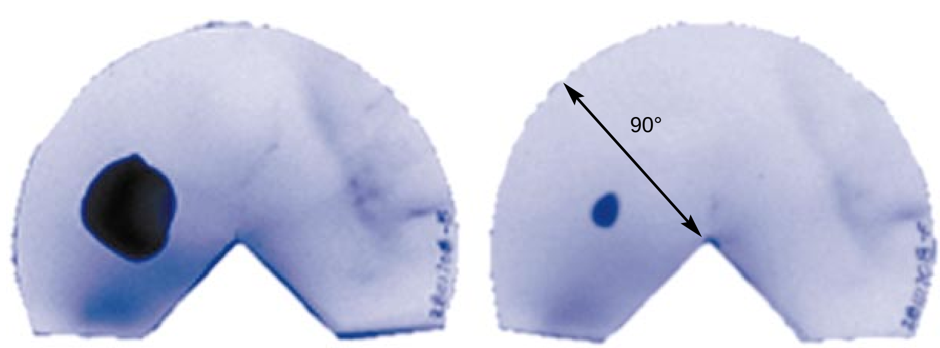
Advances in Fast Ignition

In both fast-ignitor and conventional inertial confinement fusion (ICF), laser or x-ray pulses rapidly heat the surface of a fusion target capsule, enveloping it in plasma. The fuel inside the target is compressed by a rocketlike blowoff of the surface material. In conventional ICF, the plasma must remain highly symmetrical and spherical during implosion if the fuel is to reach 20 times the density of lead and ignite at 100 million degrees. This level of symmetry requires enormous energy and precision from the laser.

In comparison, in fast-ignitor ICF, at the moment of maximum compression, a laser pulse plows through the plasma to make a path for another very short, high-intensity pulse to reach and ignite the compressed fuel. Neither spherical geometry nor the formation of a central hot spot is required in this approach. In theory, fast ignition reduces both the laser energy and precision requirements for achieving ignition.

But fast ignition faces its own challenges. The spot to be heated must be large enough to ignite all the fuel, but not so large as to waste energy. Electrons must be driven far enough to penetrate the plasma and heat the ions

(a) 200-micrometer-thick tantalum layer (b) 600-micrometer-thick tantalum layer



Radiochromic film images show a highly collimated beam of protons penetrating different layer thicknesses of tantalum. The beam cone angle narrows for protons of higher energy that penetrate greater thicknesses of tantalum. In (a), protons with greater than 17-megaelectronvolt energy penetrate a 200-micrometer-thick tantalum layer, and in (b), protons with greater than 30-megaelectronvolt energy penetrate a 600-micrometer-thick tantalum layer.

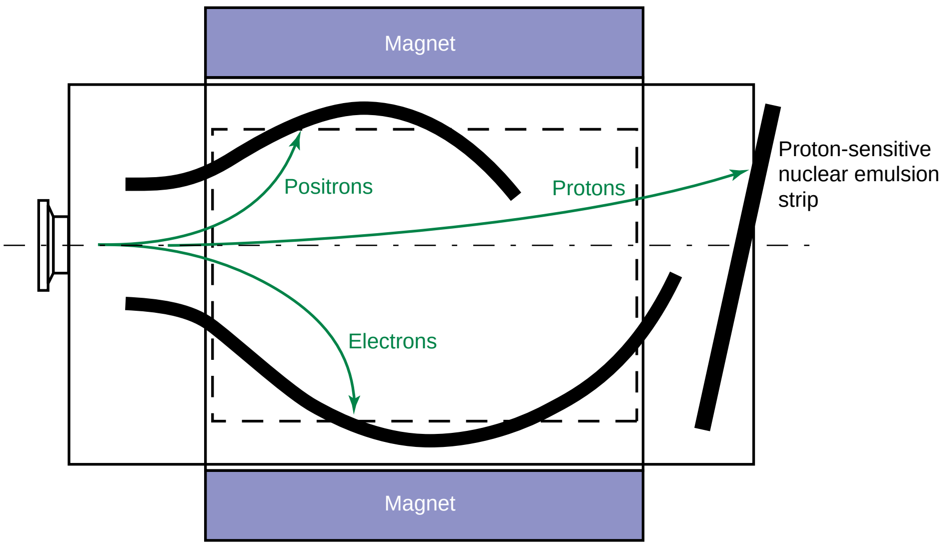
on the surface of the dense cores, but not any farther.

The short, high-intensity pulses of the Petawatt were created specifically to study the delivery of electrons to the right spot. But the Petawatt's designers knew that its kilojoule of energy was not enough for ignition. A much more powerful laser will eventually be needed.

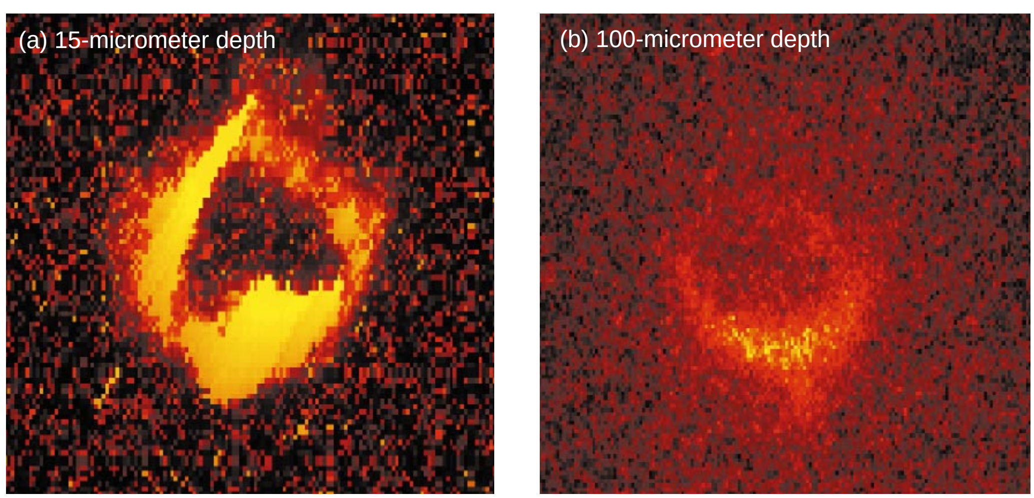
Experimenters examined the efficiency of energy transfer from a short-pulse ignitor beam to the ignition spark via the surrounding plasma. Specifically, they sought evidence for the heating of electrons in solid targets. One experiment used a sophisticated neutron detector that recorded neutrons produced by deuteron–deuteron thermonuclear fusion, indicating heating of the ions to temperatures in the 0.5- to 1-kiloelectronvolt range. These temperatures are not enough for ignition but are higher than temperatures previously seen.

Another experiment looked at aluminum foil sensors buried in polystyrene targets. When heated to about 300 electronvolts, the buried foil emitted x rays. Of particular interest were pinhole camera images of the x rays from the aluminum, which showed an annular (circular) pattern of heating with an 80-micrometer diameter. Images from the rear surface showed a similar annulus up to 100 micrometers deep inside the solid target, and some emission was also observed at a 200-micrometer depth. These data strongly suggest heating in a well-focused pattern, as predicted by theoretical modeling.

The existence of the proton beam, which was discovered only during the final weeks of Petawatt experiments, may change the fast-ignitor picture. Unlike electrons, whose energy diminishes with distance, protons deliver most of their energy where the beam stops. Because of their greater mass, protons are less easily deflected as they pass through the intervening plasma and may therefore be transported to the thermonuclear fuel much better than electrons.



To verify that the beam measured in the previous figure was composed of protons, a spectrometer was used to separate electrons, positrons, and protons. The more massive protons were deflected less by the magnets and passed through to a proton-sensitive nuclear emulsion strip. There were so many protons that the strip was turned black.



Results of an experiment to examine energy transport in dense materials (efficient energy transport is crucial to fast ignition). Shown are pinhole camera images of x rays emitted by heated aluminum sensors buried in polystyrene targets. The heating showed an annular (circular) pattern at a 15-micrometer depth, similar to the annulus seen at 100 micrometers inside the solid target. This suggests the heating had a well-focused pattern, as predicted by theoretical modeling.

Laser-Driven Radiography

The use of petawatt-class lasers for the production of high-energy x rays had been proposed a number of years before the Petawatt was built. The intense, ultrashort pulse of the Petawatt was expected to yield large doses of high-energy x rays, possibly enough to compete with the electron beam accelerators that are now used for x-radiography of explosively driven devices such as Livermore's Flash X Ray (FXR) facility at Site 300 and the Dual-Axis Radiographic Hydrotest Facility (DARHT) currently under construction at Los Alamos National Laboratory.

A laser-driven source would have several advantages over an accelerator. It would be simpler in design and less expensive for taking radiographs of a single experiment from several views. It would also achieve higher spatial and temporal resolution than accelerators can provide.

During experiments to examine the Petawatt's x-ray spectrum, photonuclear reactions (nuclear breakdown induced by hard x rays) were first seen. As described previously, the focused light of the Petawatt was so intense that it caused electrons in a gold target to generate many hard x rays. These x rays produced photonuclear reactions in almost all materials associated with the target assembly and vacuum chamber.

The photonuclear data showed that the Petawatt's x-ray spectrum ranged as high as 60 megaelectronvolts. Monte Carlo modeling estimated that from 40 to

The Largest Diffraction Gratings

In the 1990s, when chirped-pulse amplification required pulse compression gratings of sufficient size, optical quality, and ability to withstand the enormous power of the Petawatt laser pulse, Livermore developed them. No facilities were capable of producing the necessary optics, and different fabrication techniques and grating designs were needed. The bold, high-risk approach taken by program leader Mike Perry, physicist Bruce Shore, laser engineer Bob Boyd, and chemical engineer Jerry Britten has resulted in a grating design and fabrication capability that is unique. It produces the largest single-element gratings in the world, up to a meter across.

Different types of diffractive optics, which have wavelength-scale surface structures, are used to manipulate light delivery and distribution. They can be either reflective like a mirror or transmissive like a lens; they can produce multiple beams or shape the beam. Diffraction gratings can stretch or compress a broadband laser pulse, sample a beam of light, or steer it. Fresnel (diffraction) lenses help to focus light beams, and phase plates shape beams and homogenize them. Diffractive optics can be made on thin, lightweight substrates and yet can have very high efficiency.

In the Livermore fabrication process, the substrate is first polished and made very flat. A layer of photoresist is then applied. The thickness of the photoresist layer may be less than a micrometer or as much as 30 micrometers, depending on the use for the optic. For gratings, interference lithography or a mask is used to expose a layer of photoresist and create a groove pattern. The finer the groove pattern—up to 3,000 lines per millimeter—the more light will be dispersed by the optic. By carefully controlling the photoresist type and the exposure and development steps, a variety of groove profiles can be produced. A "curved" optical component can even be made out of flat glass by curving the grooves or varying the spacing of the grooves.

Following production of the grating pattern in the photoresist, the component is either gold-coated for metal gratings or ion-beam etched for multilayer or transmissive optics.

Livermore's Diffractive Optics Group produced about 50 gratings last year. Currently, they are fabricating optics for laser facilities in the U.S. and several other countries, including the diffractive optics for petawatt-class lasers under construction in Germany, Japan, and England. They are also developing diffractive optics for the National Ignition Facility and lightweight optics to be used in various space applications.

In this booth, interference lithography exposes a layer of photoresist in a groove pattern.

50 percent of laser energy might be converted to electrons, which could yield an x-ray dose comparable to that achieved with the FXR.

Radiographs of objects with a density greater than 150 grams per square centimeter exceeded the resolution achievable with accelerator sources. Although the achievable dose was comparable to some accelerator-based x-ray sources, it was less than that achievable with advanced, large-scale induction accelerators such as DARHT.

Petawatts around the World

Other researchers around the world have not been blind to the new regime of physics that the Petawatt laser has produced. Scientists in Germany, England, France, and Japan are developing petawatt-class lasers of their own. Livermore will provide the diffraction gratings used to stretch and compress the pulse for many of these lasers. At the same time, Livermore scientists are planning collaborative research projects so they can continue to perform experiments on these powerful lasers.

—Katie Walter

Key Words: chirped-pulse amplification, diffractive optics, fast ignition, laser cutting, Nova, Petawatt, proton beam.

For Further Reading

1. M. D. Perry and G. Mourou, “Terawatt to Petawatt Subpicosecond Lasers,” *Science,* Vol. 264 (1994), p. 917.
2. M. D. Perry et al., “Petawatt Laser Pulses,” *Optics Letters*, Vol. 24 (1999), p. 160.
3. B. Stuart et al., “Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses,” *Physics Review Letters*, Vol. 74 (1995), p. 2248.
4. M. H. Key et al., “Hot Electron Production and Heating by Hot Electrons in Fast Ignition Research,” *Physics Plasmas*, Vol. 5 (1998), p. 1966.
5. T. E. Cowan et al., “Photonuclear Fission from High-Energy Electrons from Ultra Intensive Laser–Solid Interactions,” *Physics Review Letters*, Vol. 84 (2000), p 903.
6. S. P. Hatchett et al., “Electron, Photon and Ion Beams from the Relativistic Interaction of Petawatt Laser Pulses with Solid Targets,” *Physics Plasmas*, Vol. 84 (in press).

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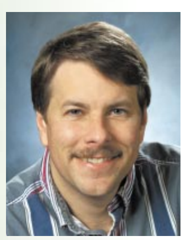
About the Scientist



MICHAEL PERRY joined Lawrence Livermore National Laboratory as a physicist in October 1987. He is a graduate of the University of California at Berkeley with a B.S. in both nuclear engineering and chemical engineering, an M.S. in nuclear engineering, and a Ph.D. in nuclear engineering–physics. He is currently associate program leader for Short-Pulse Lasers, Applications and Technology in the Laser Programs Directorate. He has authored more than 100 professional publications on the development and use of high-power lasers and diffractive optics.

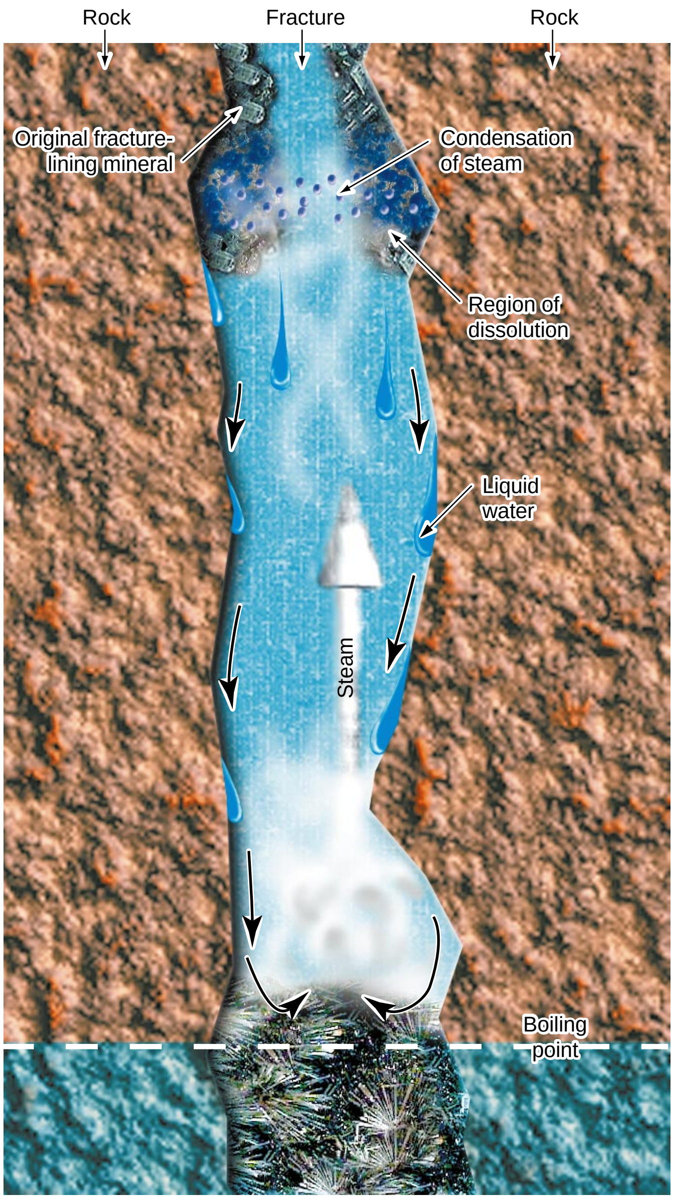
Building a Virtual Time Machine

A new computer code taps the world's most powerful computers to show how buried nuclear wastes would affect the geology of Yucca Mountain.

ONE of the most nagging technical challenges facing America's nuclear power industry is the disposal of its nuclear wastes. Likewise, the long-term success of many programs in the U.S. defense complex ultimately depends on the safe and secure disposal of high-level nuclear waste. Currently, both the civilian and defense sectors maintain their waste at locations across the country while the Department of Energy works to establish a permanent underground repository.

The only candidate site for a national high-level nuclear repository is Yucca Mountain, Nevada. (See box on p. 16.) The DOE has spent about $7 billion to date assessing the characteristics of this arid terrain for its suitability as a repository. This effort involves more than a thousand experts, including teams of geologists, materials scientists, engineers, and computer scientists from Lawrence Livermore, who are researching the site's geology and testing materials for making waste storage containers to be buried in underground tunnels. (See *S&TR*, July/August 1997, pp. 8–9, and *S&TR*, March 1996, pp. 6–16.)

While this work proceeds, scientists also need a way to accurately predict the potential repository's likely evolution over a lifetime of 100,000 years or more, including the Performance Confirmation Period of the first 100 years. "One of the biggest challenges of the Yucca Mountain project is determining how the mountain will respond to the tremendous amount of heat generated by the buried waste and if any of those geologic responses will result in the waste packages getting wet," says Livermore geochemist Bill Glassley.



Water vapor or steam in the vicinity of buried wastes will likely travel tens of meters before condensing on fractures in cooler areas. The condensed water may dissolve small quantities of the minerals lining the rock's pores and fractures (see upper part of fracture). As the water flows down toward the waste, it may also precipitate other dissolved minerals. Over time, the precipitated minerals may accumulate and seal the fracture (see lower part of fracture). The scale of this reaction process could range from a few centimeters to tens of meters.

Constructing a code to simulate the geologic evolution of a nuclear waste repository has long seemed an impossible task, for two reasons. The required computer horsepower was unavailable, even in the most powerful computers. And the software to accurately reflect all of the interweaving and evolving physical and chemical reactions of a repository also did not exist.

But now a 10-person team, supported by Laboratory Directed Research and Development funds and taking advantage of a new generation of DOE supercomputers, has constructed a code that models in unprecedented detail the likely evolution of the geochemistry and hydrology of a repository at Yucca Mountain. The Livermore team, headed by Glassley and applied mathematician John Nitao, is composed of geochemists, computer scientists, a physicist, and an ecologist. Together, the researchers have in essence developed a virtual time machine to simulate the extraordinarily complex interaction of the heat from nuclear wastes with the subsurface environment over thousands of years.

The preliminary results from dozens of simulations show how the code provides a rigorous tool for tracking the interplay of water (both liquid and vapor), heat, carbon dioxide, and chemical reactions within the repository's fractured rock. The simulations also show how the code can help determine the effect of different strategies for arranging waste packages in tunnels and whether they will come into contact with water.

Desert Rock Is 10 Percent Water

At first glance, it may seem strange that scientists are concerned about the flow of water in a desolate desert that experiences summer temperatures up to 50°C. However, Yucca Mountain is formed from volcanic rock called tuff, whose principal chemical constituent is silicon dioxide. Like virtually all rocks, the tuff contains water in its microscopic pores, in this case about 10 percent by volume. What eventually happens to this water is of intense interest because the waste packages must remain as dry as possible to help avoid corrosion and prevent their contents from leaching out. Scientists are particularly concerned about the changes in the vicinity of waste-emplacement tunnels because fractures in the rock are the principal pathways for water to enter—and leave—the tunnels.

Glassley says that it is a certainty that the intense heat from the waste will evaporate or boil off the water trapped in the rock immediately surrounding the waste packages. The water vapor or steam will likely travel up to tens of meters before condensing on fractures in cooler areas. The condensed water may dissolve small quantities of the minerals lining the rock's pores and fractures.

Gravity will likely cause some of the water to flow back down toward the emplaced waste, where it will evaporate or boil off once again. On its downward journey, the water may also precipitate other dissolved minerals if their concentrations are sufficiently high. This cycling may be repeated hundreds or thousands of times. The structure of the rock's pores and fractures will thus be modified by steam and liquid water moving through them, as well as by simple expansion and contraction in response to the intense waste heat. These changes, in turn, will alter the rate at which water moves through the rock.

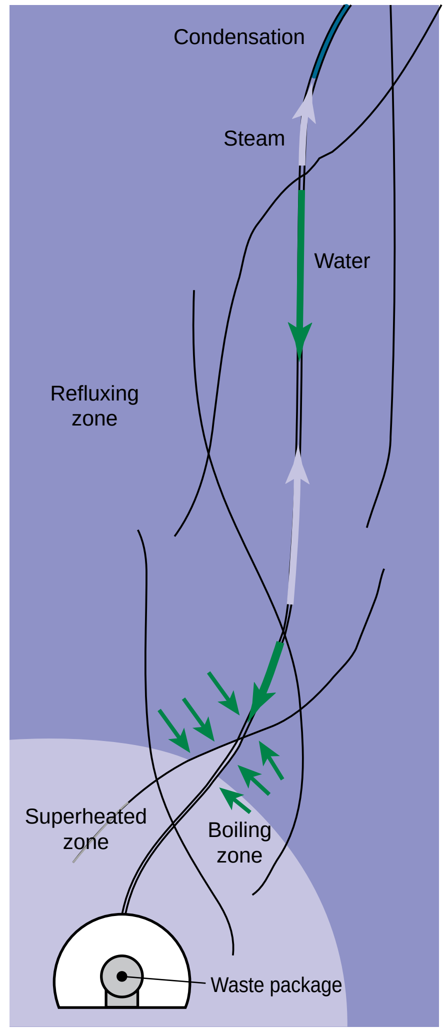
"You end up with the water changing the rock chemistry, which changes where the water moves, which changes the chemistry again. It's a strongly coupled system," says Glassley.

Over hundreds and thousands of years, some of the continuing processes could seal fractures in the rock. Or the continuing reactions could increase the opening of the cracks, producing a natural drainage system to any water and eventually leading to the water table far below.

"The two possibilities have very different implications important to waste package leakage, although the probability of such a failure is very low," says Glassley. If the water sealed the rock fractures above a tunnel, it could increase the probability that radionuclides from a leaking waste package would not leave the immediate environment, because water would be prevented from getting into tunnels. Sealed fractures below a tunnel could lead to ponding of water in the tunnel itself. If the fractures were enlarged below the tunnel, the contents of a leaking package could, over thousands of years, make their way to the water table several hundred meters below, assuming water were to enter the package. Or, depending on where the major cracks formed, they might provide a throughway for condensed or percolating water to escape the surrounding area without contacting a waste package.

All Processes Must Be Coupled

Without a realistic simulation of a nuclear repository, it is difficult to predict if water is likely to reach waste packages, and if so, when during the repository's lifetime and exactly where in the tunnels it would likely do so. A detailed simulation requires the ability



Gravity will likely cause some of the condensed water to flow back down toward the emplaced waste, where it will evaporate or boil off once again. Such cycling may be repeated hundreds or thousands of times over many centuries.

to calculate how heat and water (and steam) migrate, and how chemical reactions occur over thousands of years. It requires simultaneously calculating hundreds of independent chemical, mechanical, and physical variables at millions of locations. The calculations must be repeated hundreds to thousands of times to track changes that occur over time.

"Until recently, we couldn't even begin to think about simulating what will go on at the mountain because we'd first need a code that integrated chemistry, hydrology, and heat," says Glassley. "These processes cannot be studied individually; they must be studied together to understand the

All Roads Lead to Yucca Mountain

Experts agree that the best method for disposing of highly radioactive materials is to place them deep underground. For almost two decades, the search for an underground disposal site for nuclear waste has focused on the scorching Nevada desert, specifically, a place called Yucca Mountain. If it proves suitable, and if approved by federal agencies, Yucca Mountain will be the nation's first geologic repository for the permanent disposal of both spent nuclear fuel from nuclear power plants and high-level radioactive waste from nuclear weapons production.

Yucca Mountain is located about 145 kilometers northwest of Las Vegas on federally owned land on the western edge of the Department of Energy's Nevada Test Site. Currently, it is the only site being evaluated for suitability as a potential underground repository. It is a candidate because of its long distance from any large population center, its dry climate, its deep water table, and the geochemical and hydrologic properties of its rock, mainly compressed volcanic ash called tuff.

Scientists are trying to determine whether radioactive waste stored in highly corrosion-resistant containers deep within the mountain and 300 meters above groundwater can be considered to be reliably isolated from the environment accessible to humans. This consideration includes the migration pathways that might be followed by any escaping radionuclides—should a waste container ever fail—the ability of the rock to trap radionuclides along these pathways, and the persistence of radionuclide migration.

Yucca Mountain in the Nevada desert is a potential location for the storage of high-level nuclear wastes.

Cylindrical waste packages, measuring 3 to 6 meters long and weighing about 50 tons apiece, would be placed lengthwise along about 50 horizontal tunnels, called drifts, each stretching about 1 kilometer. During the repository's first century of operation, called the Performance Confirmation Period, scientists would track the short-term changes in the repository and test their ability to predict the behavior of the repository, including the movement of water and gases in response to heat. The results of this monitoring would provide a database against which refinements in predictions and simulations would be measured.

Three federal agencies are involved in the project. The DOE is responsible for the site evaluation, construction, management, and operation of the potential geologic repository; the Environmental Protection Agency is responsible for developing standards to protect public health and the environment; and the Nuclear Regulatory Commission is responsible for issuing the required licenses to dispose of the waste.

More than 15 years of research has gone into characterizing the site to determine its suitability as a repository. Lawrence Livermore scientists, who have been involved in the nation's nuclear waste disposal programs since the late 1970s, have participated in the Yucca Mountain project from the start. Livermore scientists have the responsibility for determining the Engineered Barrier System materials that comprise the waste package, drip shield, and backfill. They are also responsible for defining the environment that the barrier system will experience over time, including the effects of heat on that environment.

In December 1998, DOE issued a Viability Assessment, stating that the agency believes Yucca Mountain remains a promising site for a geologic repository. The overview acknowledges that uncertainties remain about key natural processes, the preliminary design, and how the site and design would interact. When the characterization work is completed next year, the Secretary of Energy will decide whether to recommend the site to the President.

With adequate funding for completion of scientific and engineering work needed to support the licensing process, the first waste could be placed in a repository by 2010. Future generations will decide when it should be closed and sealed.

evolution of the repository." Such a code did not exist, although several institutions were working on one.

Furthermore, the raw computational power to run such a complex code did not exist. But the Accelerated Strategic Computing Initiative (ASCI)—supporting DOE's Stockpile Stewardship Program to keep the U.S. nuclear stockpile viable—brought about a new generation of computers. These computers made running such a code feasible for the first time.

Livermore's Blue Pacific supercomputer, one of the key ASCI machines, uses 1,464 nodes or individual computers, each of which has four processors, for classified applications. Blue Pacific's separate unclassified platform, which the Yucca Mountain team uses, houses an additional 352 nodes containing 1,408 microprocessors. By tying the microprocessors together, Blue Pacific drastically reduces processing time to solve formerly intractable problems from months or even years (on a typical workstation) to several hours or less. "The machine was a big motivator to develop a comprehensive code," says Glassley.

They Started with NUFT

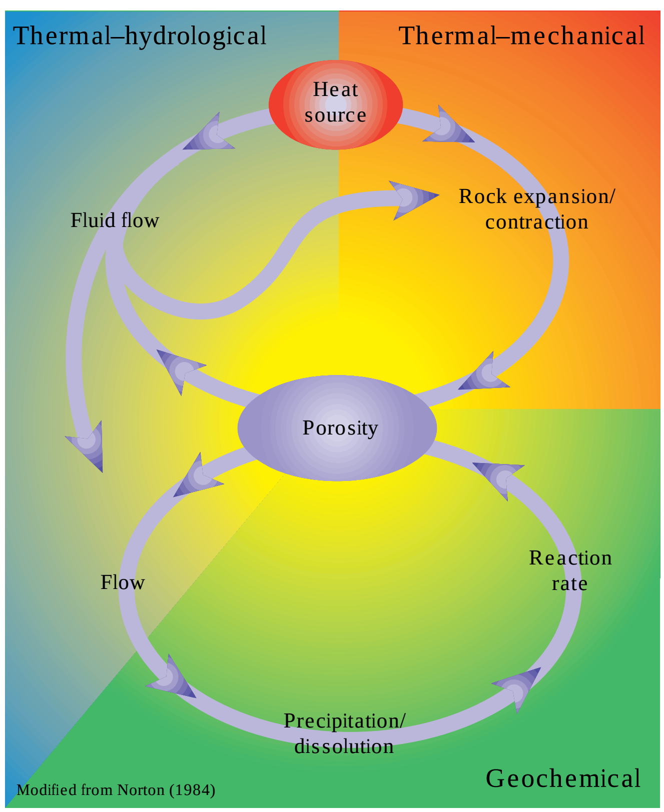
Beginning in 1998, the team embarked on writing a code that would couple heat, water, and chemical processes and take advantage of Blue Pacific's processing ability. They chose a well-regarded program called NUFT (non-isothermal unsaturated flow and transport) that was developed in the early 1990s by Nitao.

A particularly flexible code, NUFT was used during an experiment at the Nevada Test Site in 1994 to determine if a clandestine nuclear test could be detected by gases moving toward the surface. (See *S&TR*, Jan/Feb 1997, pp. 24–26.) It was also used to simulate the cleanup of underground wastes at Visalia, California, where it made accurate predictions about the success of Livermore's promising dynamic stripping cleanup technology. (See *S&TR*, May 1998, pp. 4–11.)

The code is currently being used by Yucca Mountain researchers to predict the temperature evolution surrounding buried waste and to predict how water will likely enter tunnels over the eons. While NUFT does an excellent job simulating the temperature and physics of water flow, it does not account for chemical reactions and how they modify rock fractures and pores. Nitao and computer scientist colleagues spent two years upgrading the code to reflect chemical reactions and linking chemical reactions to equations describing the transport of heat and water.

In the earth sciences community, observes Glassley, simulating chemical reactions, heat transport, and flow of liquids and gases is "a big deal" because it depends on a host of environmental factors. Simulating chemical reactions is particularly important for the Yucca Mountain project because a host of chemical reactions can take place in the tuff and its fissures, cracks, and pores that determine the flow of water. Furthermore, the waste packages will employ highly corrosion-resistant alloys, and each alloy will have different reactions with water and dissolved rock minerals. Understanding what minerals will be present to react with the waste packages is essential in predicting a response.

Simulating the likely chemical reactions at Yucca Mountain was a particular challenge. The most difficult problem was representing the kinetics of mineral precipitation in the region where boiling occurs, because large



Realistically simulating a nuclear repository requires the ability to couple the continuous interplay of heat, chemistry, water flow, and rock mechanics. Porosity and permeability are the fundamental variables that link these processes.

chemical changes can occur there in very short time periods. Standard reference data about chemical reaction rates are not applicable for conditions at the boiling point of water, which may be the conditions near buried waste packages. “We spent a lot of time figuring out how to write equations that would accurately describe reactions in these extreme environments,” Glassley says.

Fractures Made More Real

Another challenge was making sure the code simulated minerals dissolving and precipitating along the insides of fractures within the rock. A typical code represents a rock fracture as two smooth plates separated by some space. But real fractures are rough, twist around, and directly affect the rate of water movement and the consequent mineral dissolution. The team’s code incorporated a more realistic representation of fractures.

With code writing complete, the team compared the code’s chemistry predictions to results from experiments conducted at Livermore. “We needed to check how we represented water interacting with the rock to make sure we were getting the chemistry right,” says Glassley. “We found the code to be very accurate.”

The team had to adapt the program to run on Blue Pacific. Fortunately, Livermore computer scientists have extensive experience adapting codes to run efficiently on enormously powerful supercomputers. The code can also be run on workstations, and the team is particularly eager to distribute it to other geochemists when it is complete. Glassley cautions recipients, however, that particularly complex problems will take a very long time on anything short of a supercomputer.

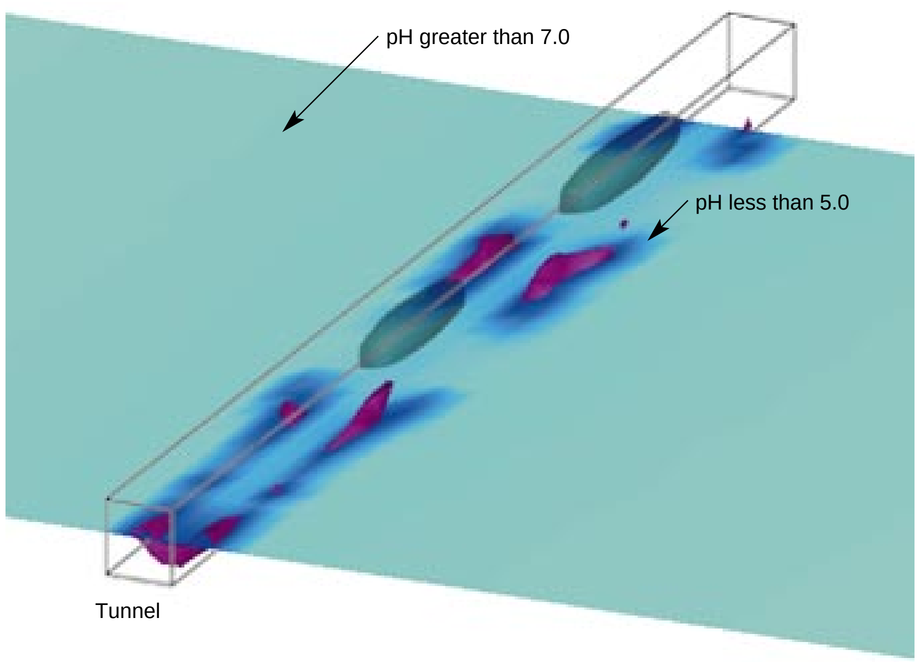
Glassley expects that the code will prove highly useful in evaluating Yucca Mountain in its Performance Confirmation Period. The code can be tested easily as it simulates specific changes that are likely to occur during the first 100 years. Early changes include a rise in the rock temperature surrounding the tunnels and an increase in carbon dioxide in rock pores associated with steam traveling through them. “The Yucca Mountain project wants to make sure what is seen in the first several decades of repository operation is consistent with our code and others that scientists plan to use,” says Glassley.

Complex Interplays

Most of the preliminary simulations conducted with the code have focused on a hypothetical waste emplacement tunnel more than 200 meters below the surface. This virtual tunnel contains separate packages of nuclear power plant wastes that are as hot as 200°C and nuclear weapon production wastes that are relatively cool at 60° to 90°C.

After about 500 years, significant and irreversible changes to the rock near the waste are apparent. Water that has condensed above the upper parts of the tunnel cause the formation of a dome that partially seals the rock fractures. The hotter waste packages cause more extensive sealing than the cooler packages. What’s more, the partially sealed domes occur farther away from the hot waste than from the cooler waste.

“The code is really giving us snapshots in time of the openings and



Three-dimensional simulations depict chemical changes after more than 1,000 years in the vicinity of waste packages. In this case, two emplacement tunnels, each with eight waste packages with different heat outputs, were represented. The red volumes enclose those regions in which the pore and fracture waters are somewhat acidic (pH less than 5.0). The blue areas indicate regions where the water is neutral to slightly alkaline (pH greater than 7.0).

closings of rock fractures," explains Glassley. Many findings, such as the complexity of the partially sealed regions, are surprising. Also unexpected is the finding that after about 3,000 years, the domes are still present, but a film of liquid water covers the cool waste packages. Presumably, the water has been driven off slowly from near the hot waste and has come to settle over the cooler waste. "Discovering this water shows how difficult it is to make accurate predictions without a strong simulation tool," Glassley says.

Additional simulations show that the extent of fracture sealing and the occurrence of moisture near the cooler packages depend on the exact placement of the waste packages. Numerous strategies are possible to minimize moisture near the cooler waste packages, including combining civilian and defense waste so the temperature is roughly the same above all waste packages and placing the packages closer together to boil off any water that might collect on the cooler ones.

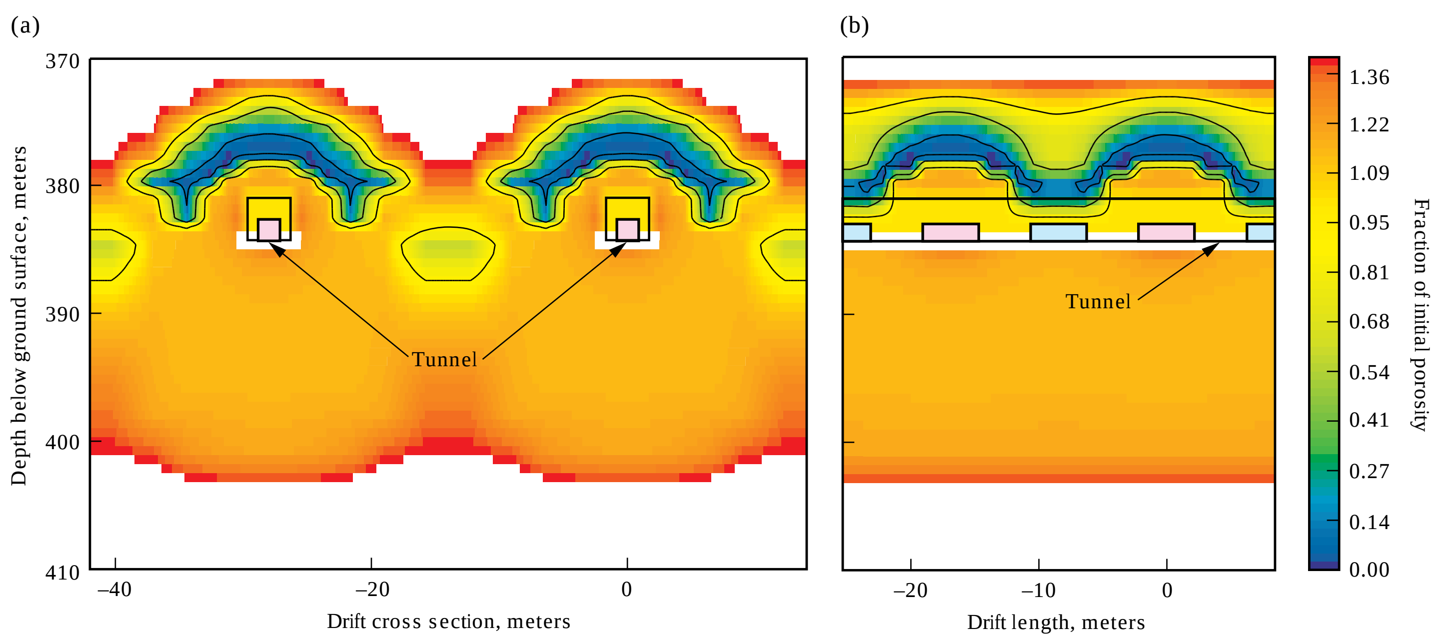
Looking to the Future

The team has conducted short simulations using more than a thousand of the 1,408 microprocessors on the Blue Pacific's unclassified platform. A new series of simulations, scheduled to begin this summer, will require all of the machine's unclassified capacity for extended times. The new simulations will depict multiple tunnels, with each tunnel containing waste packages generating different amounts of heat. The simulations will examine the effects over time of interaction among arrays of waste packages.

The team also plans to increase the number of chemical reactions the code mimics, including those involving radionuclides that could possibly leach out of containers—should there be a breach of the container—over thousands of years. Scientists believe that minerals in the rock could retard the movement of radionuclides dissolved in water, either through chemical reactions or by adsorption onto the rock surface.

Obtaining access to more powerful visualization capabilities is also high on the to-do list. "A thousand processors working for several hours will produce far too much information to contain on a single computer screen," says Glassley. The team hopes to use a power wall, which is an array of monitors pieced together into one giant monitor, to project the true wealth of detail generated by the code.

But viewing even a multitude of computer screens remains a two-dimensional experience. The team also hopes to use three-dimensional visualization tools currently being acquired at Livermore. "With 3D glasses, we'll be able to seemingly fly into the tunnels and look around at the waste packages," says Glassley.



(a) Two-dimensional cross section through two tunnels shows the formation of domes overlying the "hot" (pink) waste packages from spent nuclear power plants. (b) A lengthwise cross section of a single tunnel simulates both "cool" (blue) waste packages from defense production and hot waste packages. The hot waste clearly causes more extensive sealing than does the cool waste. Also, the domes occur farther away from the hot waste. After about 3,000 years, the domes are still present, but a film of liquid water covers the cool packages.

The future may bring other important assignments for the code. Two obvious applications are in helping to manage underground aquifers and cleaning up contaminated groundwater. The team is also in discussion with a U.S. petroleum company to use the code for oil exploration. Adapting the code for the oil industry should not be particularly difficult because it only requires adding an additional liquid—oil—with its different properties and tracking it as it moves through underground strata. The code is currently structured to do exactly this kind of simulation.

One intriguing application is for advancing the understanding of how earthquakes are triggered. Some geologists believe that fluids, specifically deep underground water, play an important role in fault rupture. "We think the code will be able to test this theory," says Glassley.

In the near term, however, the team is focusing its efforts on strengthening the scientific understanding of how America's potential first underground nuclear waste repository will perform in the near—and far—future.

—Arnie Heller

Key Words: Accelerated Strategic Computing Initiative (ASCI), Blue Pacific, computer simulation, Engineered Barrier System, Nevada Test Site, nuclear waste repository, NUFT (non-isothermal unsaturated flow and transport), Performance Confirmation Period, power wall, Yucca Mountain.

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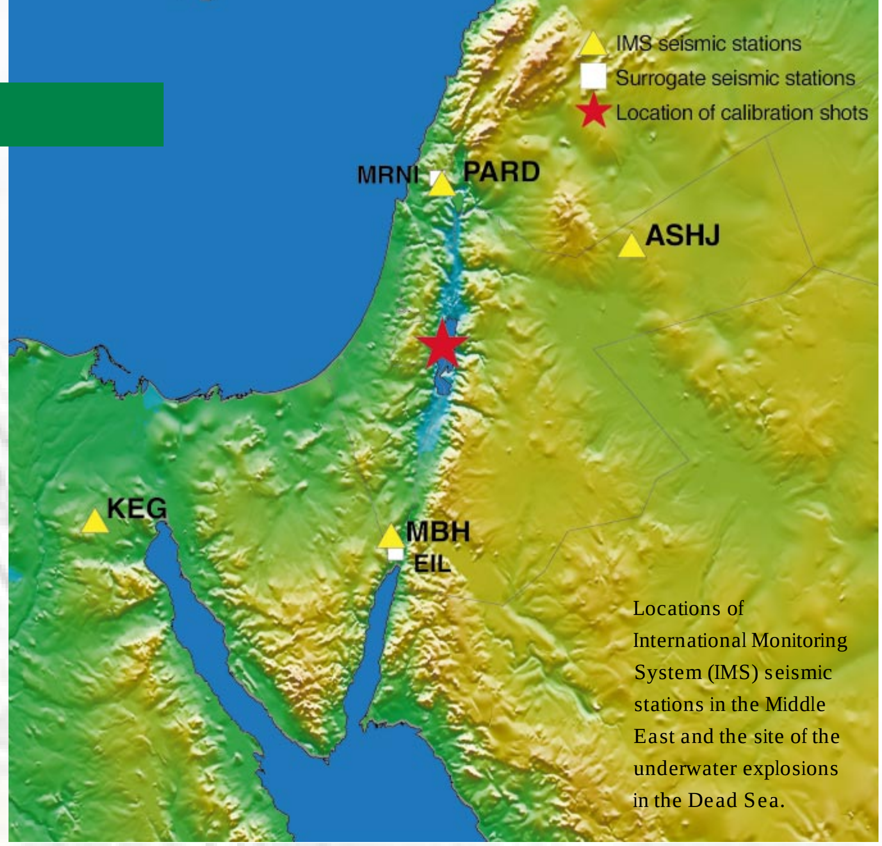
About the Scientist

BILL GLASSLEY received his B.A. in earth science from the University of California at San Diego and his M.S. and Ph.D. in geochemistry from the University of Washington, Seattle. For ten years, he was a professor and researcher at Middlebury College in Vermont. He joined Lawrence Livermore in 1986, where he is a geochemist in the Earth and Environmental Sciences Directorate.

For the modeling and simulation work on the Yucca Mountain project, Glassley and Livermore applied mathematician John Nitao led a multidisciplinary team of scientists and engineers that included Thomas Boulos, Mary Gokoffski, Charles Grant, James Johnson, James Kercher, Jo Anne Levatin, and Carl Steefel.

Dead Sea Explosions Trigger International Cooperation



Locations of International Monitoring System (IMS) seismic stations in the Middle East and the site of the underwater explosions in the Dead Sea.

THE Middle East has long been a region beset with tension, if not outright warfare. It is ironic, therefore, that a series of underwater explosions set off in the Dead Sea last November may, with the assistance of Lawrence Livermore seismologists, help to reduce tensions in the area and spur cooperative ventures on geophysical-related issues.

Conducted by the Geophysical Institute of Israel, the explosions were cofunded by Israel and the U.S. Defense Threat Reduction Agency. The main goal was to improve monitoring of the Comprehensive Test Ban Treaty (CTBT) by calibrating Israel's two International Monitoring System (IMS) seismic stations as well as its national system of seismic monitors. Because the tests were announced well ahead of time, other Middle East nations were afforded the opportunity to calibrate their own national seismic stations and any IMS stations on their territories. The explosions will help scientists to pinpoint the location of suspicious seismic events in the area and distinguish them from other sources of seismic signals.

According to Livermore seismologist Keith Nakanishi, detecting, locating, and identifying a clandestine nuclear test poses a particular challenge in the Middle East. International stations are few and far between in the area. Also, a large number of earthquakes and mining explosions generate thousands of seismic signals annually, some quite similar to the signals that would be generated by a small underground nuclear blast.

Additional "ground truth" for the area is sorely needed, Nakanishi says. Ground truth includes seismic data from well-documented earthquakes, mine explosions, or explosions carried out for calibration purposes. Carefully gathered data from these events improve the knowledge of how regional-specific features in the Earth's crust and upper mantle affect the travel times, amplitudes, and frequencies of weak seismic signals. Such data are particularly important to accurately determine the location and origin time of the seismic sources.

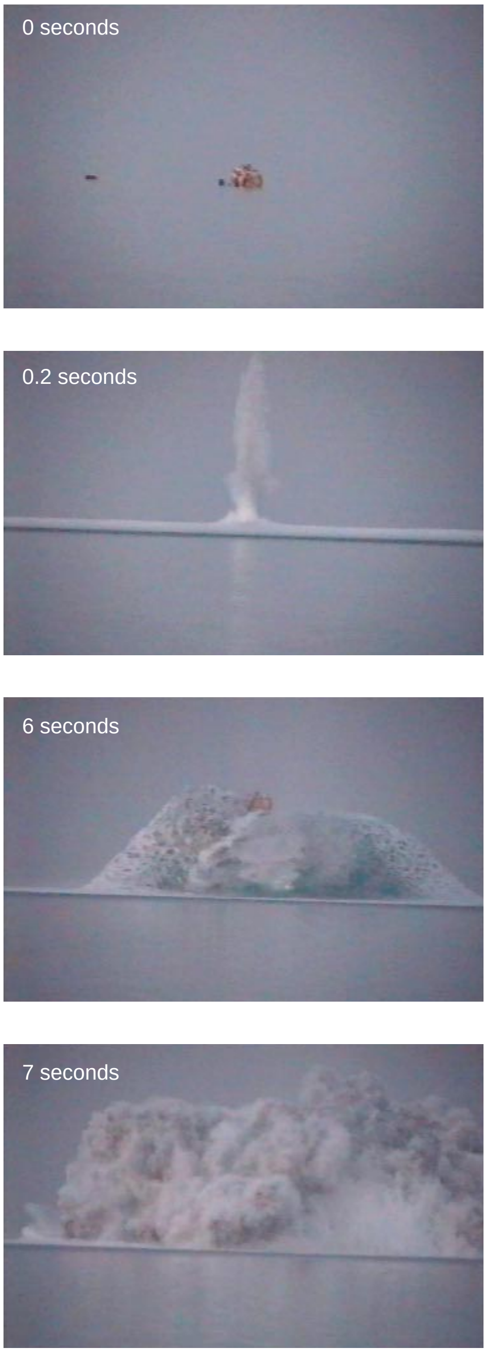
Building a Knowledge Base

For the past several years, the Department of Energy has been developing a knowledge base of regional seismic properties for the U.S. National Data Center at Patrick Air Force Base, Florida. As part of DOE's program, a team of Livermore experts is focusing on the Middle East and North Africa (called MENA) and the western part of the former Soviet Union. (See *S&TR*, September 1998, pp. 4–11, and *S&TR*, April 1999, pp. 18–20.)

The Livermore team is working to improve techniques to detect and characterize clandestine underground nuclear explosions in key areas of concern for proliferation monitoring. An important application of this technology is for CTBT monitoring. Both Israel and the U.S. have signed the treaty but have not ratified it.

For the Middle East, well-planned calibration experiments are an important means of establishing ground truth in an area whose geologic complexity rivals that of the western part of the United States. Tests conducted in water are preferable to those conducted underground, because water is an excellent medium for transmitting seismic waves. As a result, a much smaller amount of explosives is necessary for a calibration test done under water than is required for an underground test.

The Israelis detonated three underwater packages of explosives, all at the same location (about 5 kilometers from Israel's Dead Sea shores) and depth (about 70 meters below the water surface). A 500-kilogram explosive was detonated on November 8, 1999, with an approximate magnitude of 2.6 on the Richter scale, and a 2,000-kilogram explosive was detonated on November 10, with an approximate magnitude of 3.5 on the Richter scale.



Stills from a video camera show the sequence of events during the 5,000-kilogram Dead Sea explosive test captured at 0, 0.2, 6, and 7 seconds following detonation. The frame at 0 seconds shows the steel buoy used to fix the charge depth at about 70 meters.

These first two tests were conducted largely to demonstrate that underwater explosions posed no danger to people, property, or the environment. The main test, a 5,000-kilogram explosive package, was set off on November 11, producing a 9-meter-high fountain of water and an approximate magnitude of 4.0 on the Richter scale. (By comparison, a 1-kiloton nuclear explosion would produce a magnitude in the range of about 4.0 to 4.5 on the Richter scale.)

Experiments Were Well Characterized

To be particularly useful, seismic calibration tests must have well-defined locations and origin times. For the Dead Sea tests, these parameters were well determined, says Nakanishi, who attended planning meetings in Israel that focused on such requirements. The location of each test was known to an accuracy of 20 meters, the depth was established to within an accuracy of 5 meters, and the time was determined to an accuracy better than 20 milliseconds.

The explosions were recorded by the Geophysical Institute of Israel and its network of seismic stations, including two IMS stations located in the southern and northern areas of the country. The events were also recorded by a group of more than 30 smaller stations that form Israel’s national seismic network and by a few temporary stations Israel installed on the Dead Sea shores. Seismic stations in neighboring countries such as Jordan, Egypt, and Saudi Arabia reportedly also recorded the tests. The Geophysical Institute distributed data electronically to interested parties, including Nakanishi and his colleagues, within a few days.

The Livermore team is analyzing the Dead Sea data and using the results to refine the DOE’s knowledge base for the area. For their part, Israel, Jordan, and other Middle East nations are using the data to strengthen their own national means to identify the magnitude and location of any clandestine nuclear blasts and future earthquakes and to better distinguish between the two.

Nakanishi predicts that the explosions will prove as valuable for earthquake monitoring as for CTBT monitoring. “The area is riddled with faults and has a long history of earthquakes dating to Biblical times,” he says. The most dangerous fault is the Dead Sea Rift Valley fault that stretches from Syria through Israel and into East Africa, with one fault branch underlying Haifa, Israel. In 1995, an earthquake of magnitude 7.1 on the Richter scale occurred on the fault in the Gulf of Aqaba in the Red Sea near the Israeli city of Eilat.

Well-calibrated seismic networks will allow scientists to better locate the origin of future earthquakes. “By knowing what fault caused the earthquake, we’ll know what to expect in terms of aftershocks," Nakanishi explains. He notes that seismic safety has become a larger concern in the area following the strong 1999 temblors in nearby Turkey.

International Meeting to Focus on Tests

The Dead Sea tests will be the focus of a week-long international workshop to be held this spring, facilitated by Nakanishi and several Livermore colleagues. Each participating nation will share the data recorded at their seismic station. "Jordan and Israel share the Dead Sea," Nakanishi points out. "Each will bring its one-half of the coverage from the tests. By pooling the data, we'll have a full 360-degree coverage."

Nakanishi is hopeful that representatives from Saudi Arabia, Egypt, Jordan, Israel, Cyprus, Lebanon, Turkey, Kuwait, Qatar, Yemen, Oman, and the Palestine Authority will attend. The meeting has the blessing of the U.S. State Department and of the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the meeting's official sponsor.

Nakanishi says that the workshop can also help to reduce political tension. "Regional cooperation in seismology can encourage participation in other technical discussions and increase security in the area," he says. By sharing data and discussing results, participants can be assured that if clandestine nuclear testing is taking place, they would be able to quickly identify it. The data will also help characterize the area for earthquake hazard mitigation and support basic seismic research.

Livermore scientists hosted a similar workshop in 1997 in Cyprus. The focus then was the 1995 Gulf of Aqaba earthquake; interest in the earthquake was high because of its potential negative impact on economic development in the area. "It was a great opportunity for people who don't ordinarily meet to discuss matters of common interest in a neutral venue," says Nakanishi.

He observes that seismic waves respect no boundaries or political or religious beliefs. Because better understanding of ground motion helps every nation, seismology may be a contributor to lessening tensions in an area that has had more than its share of tremors.

—*Arnie Heller*

Key Words: Comprehensive Test Ban Treaty (CTBT), Dead Sea, Defense Threat Reduction Agency, Gulf of Aqaba, knowledge base, Middle East and North Africa (MENA), seismic monitoring, United Nations Educational, Scientific, and Cultural Organization (UNESCO).

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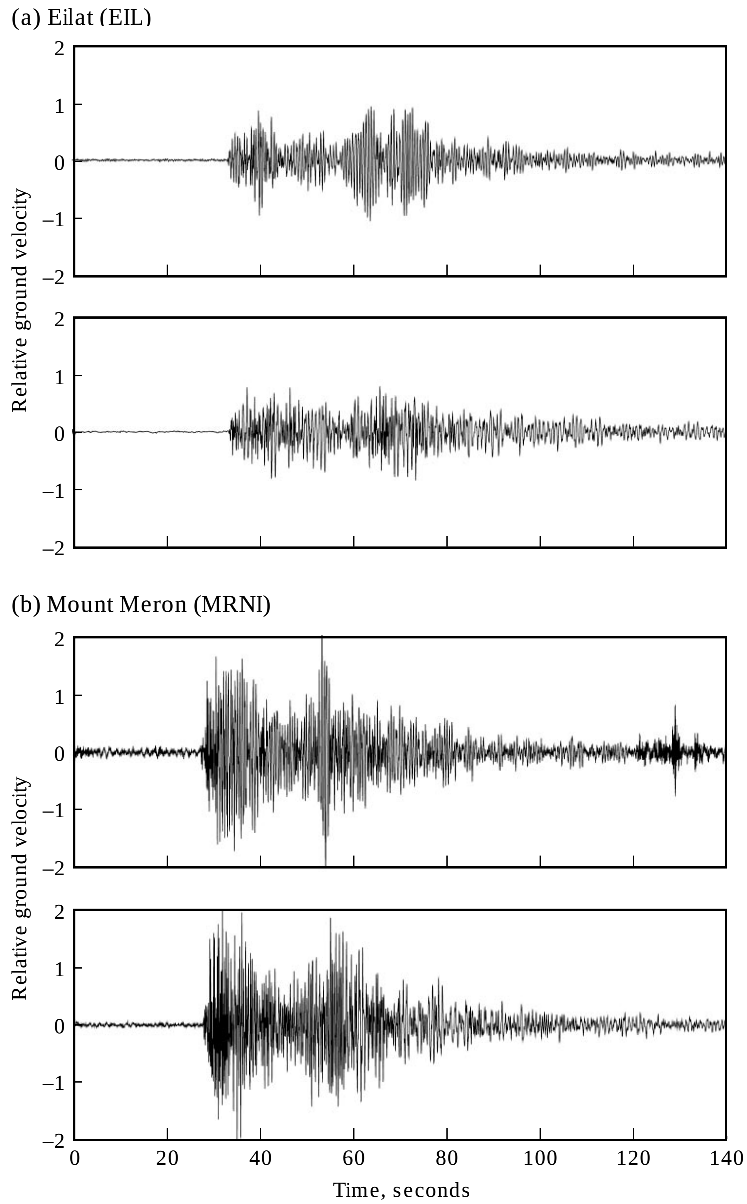

Seismograms from the second and third Dead Sea shots as recorded at Israel's International Monitoring Stations in (a) Eilat and (b) Mount Meron. The locations of these stations are shown on the map on p. 21. (The plots of the first shots are not shown because one of the stations did not provide recordings for the first day.)

Patents and Awards

Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Joseph C. Farmer	**Method and Apparatus for Capacitive Deionization and Electrochemical Purification and Regeneration of Electrodes** U.S. Patent 5,954,937 September 21, 1999	An electrically regeneratable electrochemical cell for capacitive deionization, electrochemical purification, and regeneration of electrodes. Each cell includes two end plates, each with an adjacent end electrode. An insulator layer is interposed between the end plates and the end electrodes. Each end electrode includes a single sheet of conductive material with high-specific surface area and sorption capacity. In one embodiment, the sheet of conductive material is formed of carbon aerogel composite. The cell further includes a plurality of generally identical double-sided intermediate electrodes that are equidistally separated from each other between the two end electrodes. As the electrolyte enters the cell, it flows through a continuous open serpentine channel defined by the electrodes, substantially parallel to the electrode surfaces. By polarizing the cell, ions are removed from the electrolyte and are held in the electric double layers formed at the carbon aerogel surfaces of the electrodes. As the cell is saturated with the removed ions, the cell is regenerated electrically, thus significantly minimizing secondary wastes.
Luis E. Zapata Lloyd Hackel	**Lamp System with Conditioned Water Coolant and Diffuse Reflector of Polytetrafluorethylene (PTFE)** U.S. Patent 5,971,565 October 26, 1999	A lamp system with a soft, high-intensity output that covers a large area is provided by water-cooling a long-arc lamp inside a diffuse reflector of polytetra-fluorethylene and titanium dioxide white pigment. The water is kept clean and pure with a 1-micrometer particulate filter and an activated charcoal/ultraviolet irradiation system that circulates, deionizes, and biologically sterilizes the coolant water at all times, even when the long-arc lamp is off.

Awards

The Laboratory has won two Gordon Bell prizes, the most prestigious awards in the arena of high-performance computing.

First, a laboratory team led by **William Dannevik**, collaborating with the University of Minnesota and IBM, was given the **1999 Gordon Bell Award** for its simulation of turbulence resulting from a shock wave passing through the interface of two fluids with different mass densities. The team's proof-of-principle simulation used more than 24 billion zones calculating at 1.18 trillion floating point operations per second. Dannevik is principal investigator of the Accelerated Strategic Computing Initiative's Turbulence and Instabilities Modeling Project, which developed the simulation. **Ron Cohen** is co-principal investigator. Other members of the Livermore team were: **Art Mirin** (who coordinated the simulations and the team presentation at the conference where the award was given), **Bruce Curtis**, **Mark Duchaineau**, **Dan Schikore**, **Andris Dimits**, and **Don Eliason**.

Second, Livermore was on a team that won a **special Bell Prize**, given for creating a practical simulation that achieved a new level of performance and can be applied to other uses. The award-winning project was "Achieving High Sustained Performance in an Unstructured Mesh CFD Application," a simulation of the flow of air over an airplane wing. Livermore was represented by **David Keyes**, acting director of Livermore's Institute for Scientific Computing Research and chairman of Old Dominion University's Mathematics and Statistics Department. The team also included a DOE subcontracting organization, Old Dominion University, and NASA.

Each year, no more than one-half of one percent of the current membership of the **American Physical Society** is recognized by their peers for election to the status of **fellow**. Four Laboratory scientists achieved that distinction in November 1999. **Michael Key**, Livermore's deputy scientific director for Inertial Confinement Fusion/National Ignition Facility, was cited for pioneering work in the invention of the x-ray laser, developing techniques to maximize laser output, and originating the x-ray backlighting technique. **Peter Young**, the group leader for the Inertial Confinement Fusion Program, was recognized for his research on how intense laser pulses move through plasma. Understanding the effects of intense pulses is important for controlling the laser spot and focusing laser energy on the target. **Kennedy Reed,** who directs the Laboratory's Research Collaborations Program for Historically Black Colleges and Universities and Minority Institutions, was recognized for his efforts to promote collaboration in atomic, molecular, and optical physics among U.S., European, and African laboratories, and for his success in organizing international workshops to showcase these collaborations. **Stephen Libby**, a group leader in the Defense and Nuclear Technologies Directorate, was recognized for work in three areas: high-energy physics, where he and collaborators developed a way to predict how the basic constituents of nuclei interact at very high energies; condensed matter, where he and collaborators formulated a complete theory for a key part of the quantum Hall effect (which describes electrical conductivity at very low temperatures); and plasma physics, where he has developed new x-ray lasers and applications as well as a new way to greatly speed up calculations of light-driven processes in experiments with hot, dense, ionized gases.

The Amazing Power of the Petawatt

Livermore’s Petawatt laser was the most powerful laser in the world during its three years of operation. At peak power, its shots delivered well over a quadrillion watts of power in 440-femtosecond bursts. Experiments with the Petawatt split atoms, came close to creating an electron–positron plasma, and generated a well-focused, intense proton beam—all firsts for a laser. Designed to test the fast-ignition path to inertial confinement fusion, the Petawatt also proved to be the world’s most powerful ion accelerator. Livermore’s diffractive optics fabricating facility, developed to supply optics for the original Petawatt laser, is now supplying optical components to petawatt-class laser facilities being constructed in Germany, England, France, and Japan.

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Building a Virtual Time Machine

Yucca Mountain is the nation’s candidate site for a high-level nuclear waste repository. A major scientific challenge is accurately predicting how the heat from buried nuclear wastes would affect the site’s geology. In particular, scientists need to know if geologic responses over thousands of years could cause the waste packages to get wet. A team of Lawrence Livermore researchers has constructed a code that models in unprecedented detail the likely evolution of the geochemistry and hydrology of the repository. The complex code takes advantage of supercomputers designed for DOE’s Accelerated Strategic Computing Initiative to solve formerly intractable problems. The preliminary results from dozens of simulations prove the code a valuable tool for tracking the interplay of water, heat, carbon dioxide, and chemical reactions within the repository’s fractured rock.

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Coming Next Month

Decoding the Human Genome

A report on the Joint Genome Institute’s progress in sequencing chromosomes 5, 16, and 19. The Institute will announce the completion of the draft sequence of these chromosomes this spring, a year ahead of schedule.

Also in April

- *The design of the Next Linear Collider pushes the frontiers of particle physics and cosmology.*
- *The Remote Sensor Test Range is the proving ground for nascent remote sensing technologies developed by DOE national laboratories.*
- *Using sparkle imaging—a new technique for viewing small, distant celestial objects—Laboratory astrophysicists have mapped both hemispheres of Titan, a moon of Saturn.*

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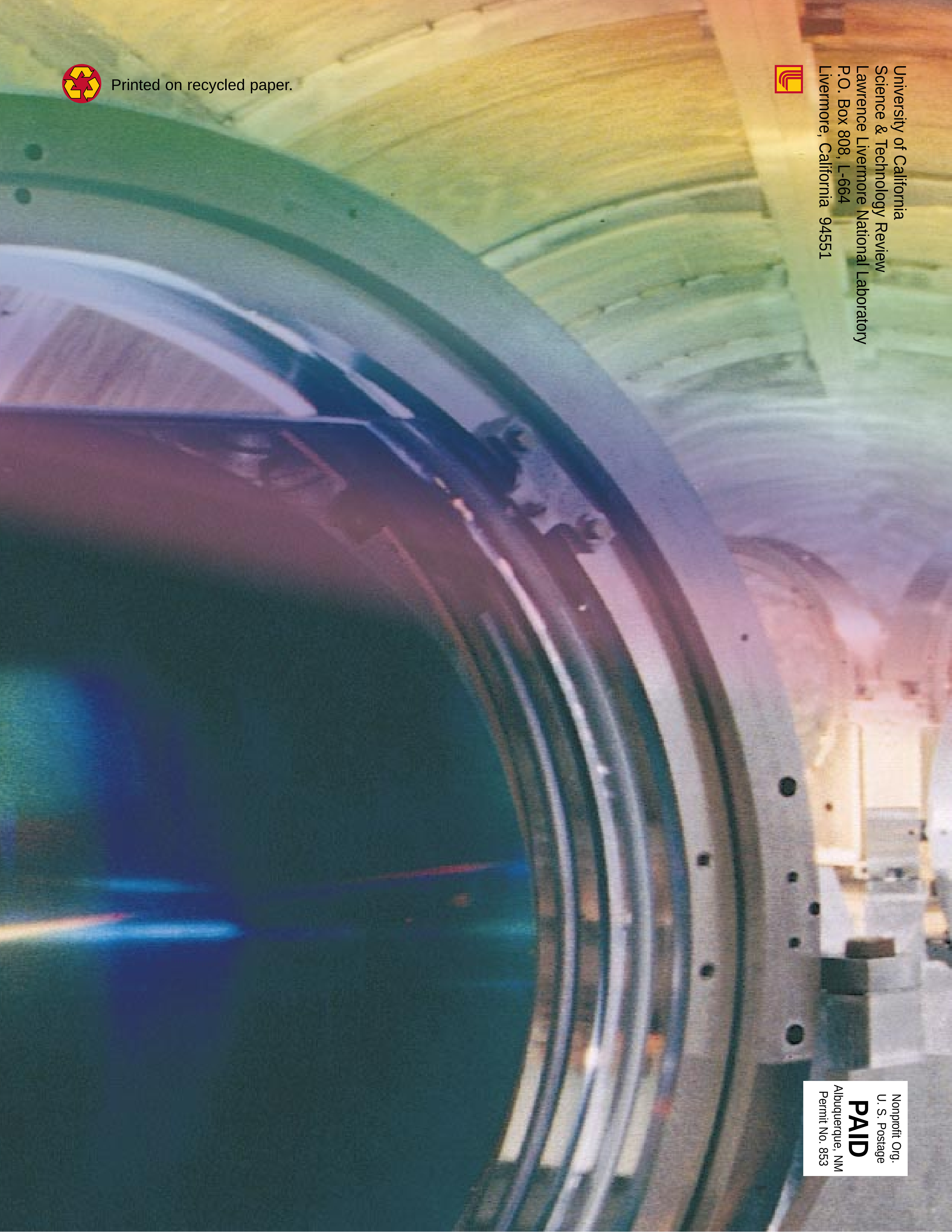

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